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CALORIMETERS AND RADIOMETERS FOR THE MEASUREMENT OF LARGE THERMAL IRRADIANCES

by

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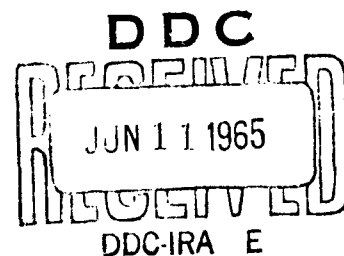
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ABSTRACT

The report is a general description of, and compilation of information about, the field type radiometers and calorimeters developed by NRDL to measure the total thermal energy and the radiant thermal power from nuclear detonations. Equations for deriving the sensitivities and time constants from physical parameters are presented and methods of construction and calibration are described. Information is also presented on laboratory sources for simulating thermal radiation from a nuclear weapon. Examples of data reduction from both field and laboratory sources are included.

SUMMARY

The Problem:

To increase the sensitivity and reliability of NRDL field radiometers and calorimeters, and to improve the methods of calibrating these instruments.

Findings:

Two instruments were constructed and evaluated: (1) A prototype vacuum calorimeter and (2) a new calibrating source consisting of banks of tungsten-iodine lamps. A considerable body of information about existing instruments and sources is included in the report to assist in the design and evaluation of such instruments. In some places new deviations were required for the equations relating the physical and thermal parameters of the instruments. Also a considerable number of modifications were made in the radiometers to increase their reliability and ruggedness.

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INTRODUCTION

The first measurements of the heat radiated by the detonation
of a nuclear device were made on the Trinity shot in New Mexico in 1945,
and some type of measurement of thermal energy has been made during
nearly every test series since then. The body of information on thermal
effects built up on the basis of these measurements is quite large and
well documented for detonations in the atmosphere near the ground.

NRDL made its first measurements of thermal radiation from a
nuclear detonation with its own instruments during the Ranger series in
early 1951, and participated heavily in succeeding operations through
HARDTACK in 1958. Instruments designed, built and calibrated at NRDL
were provided to other agencies throughout this same period, and more
than one hundred were used by the U. S. Air Force during the last
atmospheric tests in 1962.

The instruments underwent various modifications during the
first two years of their use, and a standard design was accepted in 1953.
This finalization of the design was rather arbitrary and was imposed
more by the pressure of time than by the complete desirability of the
instruments. They worked satisfactorily and the data obtained were
reliable, but they required skilled operators well versed in the
characteristics of the devices.

The thermal energy delivered by a nuclear detonation is large,
and the irradiance levels of interest were usually above one $cal/cm^2 sec$;
in many cases by more than two orders of magnitude. Because the only
existing sources of high enough energy were not particularly stable,
the calibration of the instruments required special absolute instruments

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be designed, and statistical methods used to reduce the data. Careful
attention also had to be paid to the spectral distribution of energy
from the sources, because the response of many thermal detectors is a
function of the wavelength distribution of the radiation.

With the nuclear test ban, time became available to improve
both the receiving instruments and the calibration sources. A program
was started at NRDL in Fiscal Year 1964 to re-evaluate the entire
system, both detectors and sources, with the goal of building more
simple, flexible and reliable devices including the knowledge gained in
the past ten years. This report is on the results of the first year of
this work. In addition it includes information on the standard
instruments, much of which has never been published.

BACKGROUND AND THEORY

The instruments used by NRDL are classified as radiometers
or calorimeters with the classification depending on the ratio of the
rate of heat loss from the thermal sensor to the rate of delivery of
the input energy. If this ratio is small the device is a calorimeter
and if it is near unity a radiometer. The meaning of the terms large
and small in this context is somewhat ambiguous, and in practice the
classification is made on the method of construction and the intent of
the use, with radiometers used to determine the rate of energy input
and calorimeters to measure the total energy received. Heat loss rates
from calorimeters are usually less than 5% per second and are several
hundred percent per second from radiometers. Either instrument can
change its designation, however, for appropriate thermal input times.
The thermal characteristics of some of the various types of instruments
is given in Appendix C.

CALORIMETERS: GENERAL

The field calorimeters that have been the most used NRDL instruments, are compact, rugged instruments. The sensing element consists of a 3/8 in. diameter copper button, mounted on three pointed spring clips, blackened with an electrodeposited platinum black coating on the side facing the radiation, and with a copper-constantan thermocouple fastened to the other side. A mass of copper, large relative to the button, and mounted in the case in such fashion as to be shielded from the incident thermal radiation provides a reference junction so that electrical connections may be made to the instrument with copper leads. The sensitivity of the instrument is changed by varying the button thickness, from 0.020 in. for the most sensitive to 0.125 in. for the least. The thermocouple wires are fastened to the rear side of the button by peening into small holes drilled near the button center. The button, its supports and the reference junction are mounted in a case slightly less than two inches in diameter, with a window in one end, and with appropriate O-ring seals and springs to protect the sensing elements from shock and atmospheric contamination. A schematic drawing is shown in Fig. 1.

The heat balance for a calorimeter may be written as

$$\alpha A \int_o^t H dt = M\bar{C}(T_t - T_o) + \int_o^t (h_s + h_c + h_a)(T_t - T_o)dt \qquad (1)$$

where α is the button absorptance to radiation with the spectral distribution of the incident radiation, A is the projected area of the button into the plane normal to the line between the button and the source, H is the incident irradiance, M the button mass, $\bar{C}$ the average specific heat of the button over the temperature interval T_t-T_o, T_t the temperature of the button at time t, T_o the initial button temperature and h_s, h_c and h_a loss coefficients due to radiation from the button,

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conduction losses down its supports, and convection and conduction losses through the air in the instrument. In an exact analysis, the loss coefficients are a function of temperature and time and equation (1) is not solvable. If Newtonian cooling, with the rate of heat loss directly proportional to the rise of the button temperature above its surroundings is assumed as in Reference 1, then the loss coefficients may be lumped into a single constant and a unique solution to Eq. (1) is possible. That this assumption is valid over the time interval necessary to accurately determine the total thermal energy from a weapon pulse will be shown later.

With the heat loss coefficients combined in a single constant θ (equal to the combined values of the various h's divided by $\bar{MC}$). The rate of change of the temperature of the button is

$$\frac{dT}{dt} = \frac{H}{B'} - \theta T \tag{2}$$

where B' is a calibration constant ($cal/cm^2/°C$ in the dimensions usually used) equal to $\bar{MC}/\alpha A$. If there were no losses θ would be zero and the solution to Eq. (12) would be simply

$$T = \frac{1}{B'} \int_0^T H dt = Q/B' \tag{3}$$

where Q is the total energy received prior to time t.

The temperature rise of the sensing element in a calorimeter or radiometer is measured with a thermocouple, and the output of the instrument is in millivolts. In the analysis which follows the temperature has been replaced by the thermocouple output voltage ZT with Z assumed constant. This assumption is reasonably accurate for some thermocouples, such as chromel alumel, over at least part of their range, but is rather in error for the copper-constantan couples

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used in the field calorimeters, where Z may, over the temperature range -40°C to 100°C, be evaluated from the equation $Z = 38.3 + .07T$ microvolts/°C with only a small error. Similarly, the value $\bar{C}$ has been assumed constant in the analysis, although for OFHC copper, as used in the calorimeter buttons, C is represented reasonably well by the equation $C = .0915 + 3.5 \times 10^{-5}T$ cal/g/°C. As long as the instruments are used over the same range for which they were calibrated, about 20°C to 100°C, the error due to the two assumptions is cancelled out by the calibration process, which gives a value of B $(B = B'/Z)$ which is an effective average for the temperature interval. Also, the variations in Z and C have opposite effects on B and partially compensate for each other, but for highly accurate work over temperature intervals different than the calibration interval, the values of E must be translated back to temperature by reference to the appropriate thermocouple tables, and an effective value of $\bar{C}$ chosen from the heat capacity data available in handbooks. These corrections were actually made in much of the data from field tests reported by NRDL.

It is the opinion of the author of this report that such refined corrections are seldom necessary, however. Unless they are made with extreme care they can cause more error than they correct, and they furthermore give the illusion that the accuracy of the data is significantly increased. In general, thermal data can seldom be measured with an accuracy equal to ±5%, except under ideal conditions, which never occur in the field and only rarely do so in the laboratory.

Calorimeters: Calibration

The unavoidable variations which occur in the manufacture of field calorimeters made it necessary to calibrate each instrument, before and after field use. The calibration procedure has varied

over the years, with the following rather simplified method, adopted in 1962, presently in use.

Instruments are exposed, one at a time, to a constant irradiance from a high current carbon arc source for a precisely timed period. The level of irradiance is adjusted to cause a temperature rise of about $50^{\circ}C$ in the button during this time. The output voltage is recorded by a digital voltmeter with a precision of 0.01 mv. At the end of irradiance period, the decay voltage may be recorded for about 15 seconds. Tertiary standards of precisely the same construction as the field instruments are exposed at uniform intervals during the calibration process to determine the irradiance from the arc. These tertiary standards have been calibrated against a secondary standard whose calibration related back to the NRDL absolute water flow calorimeter (Ref. 2). To minimize the effect of the unavoidable carbon arc variations, each instrument is exposed six times, and the results averaged.

At the end of the pulse, when the irradiance is zero, eq. (2) becomes

$$\frac{dE}{dt} + \theta E = 0$$

so that

$$\ln E_1 / E_2 = \theta (t_2 - t_1) \tag{4}$$

The decay constant θ can be evaluated from eq. (4) by determining two output voltages E_1 and E_2 at times t_1 and t_2 respectively on the temperature curve after the end of the thermal pulse.

During the pulse, when H is constant at a value above zero, the solution to eq. (2) is

$$E = \frac{H}{B\theta} \left[1 - \exp(-\theta t) \right] \tag{5}$$

where the notation $\exp(x)$ is equal to e^x, where e is the base of the natural logarithms. At times t_1 and t_2 during the exposure the relationship between the respective voltages E_1 and E_2 is

$$E_2 - E_1 = \frac{H}{B\theta}\left[\exp(-\theta t_1) - \exp(-\theta t_2)\right] \tag{6}$$

If θt is small, but not negligible, as is usually the case for the calorimeters actually in use, eq. (6) may be approximated by

$$E_2 - E_1 = \frac{H}{B\theta}\left[\left(1 - \theta t_1 + \frac{\theta^2 t_1^2}{2}\right) - \left(1 - \theta t_2 + \frac{\theta^2 t_2^2}{2}\right)\right]$$

$$= \frac{H}{B}\left[(t_2 - t_1) + \frac{\theta t_1^2}{2} - \frac{\theta t_2^2}{2}\right]$$

$$= \frac{Q}{B} - \frac{H\theta}{2B}\left[(t_2 - t_1)(t_2 + t_1)\right]$$

$$= \frac{Q}{B} - \frac{\theta(t_2 - t_1)}{2}\left(\frac{Ht_2}{B} + \frac{Ht_1}{B}\right) \tag{7}$$

From (5), with the same assumption about θt

$$E_1 = \frac{H}{B\theta}\left[1 - (1 - \theta t_1 + \frac{\theta t_1^2}{2})\right]$$

$$E_1 = \frac{H}{B}\left(t_1 - \frac{\theta t_1^2}{2}\right)$$

$$\frac{Ht_1}{B} = E_1 + \frac{\theta H t_1^2}{2B} = E_1 + \frac{Q_1 \theta t_1}{2B}$$

and similarly

$$\frac{Ht_2}{B} = E_2 + \frac{\theta H t_2^2}{2B} = E + \frac{Q_2 \theta t_2}{2B}$$

Substituting in (7)

$$E_2 - E_1 = \frac{Q}{B} - \frac{\theta(t_2 - t_1)}{2}\left[E_1 + E_2 + \frac{Q_1 \theta t_1}{2B} + \frac{Q_2 \theta t_2}{2B}\right] \qquad (8)$$

Q_1/B is approximately E_1 and Q_2/B is approximately E_2, so that eq. (8) may be written

$$E_2 - E_1 = \frac{Q}{B} - \frac{\theta(t_2 - t_1)}{2}\left[E_1 + E_2 + \frac{E_1 \theta t_1}{2} + \frac{E_2 \theta t_2}{2}\right] \qquad (9)$$

The maximum value for θ for the field instruments is just slightly more than 0.05 and the times t_1 and t_2 are kept short so that

$$\frac{\theta(t_2 - t_1)}{2}\left[E_1 + E_2 + \frac{\theta}{2}\left(E_1 t_1 + E_2 t_2\right)\right]$$

is not more than 10% or 15% of Q/B. Then $\frac{\theta}{2}\left(E_1 t_1 + E_2 t_2\right)$ is small compared to $\left(E_1 + E_2\right)$, and the equation for calibrating the instruments is

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$$B = \frac{Q}{\left(E_2 - E_1\right) + \frac{\theta}{2}\left(t_2 - t_1\right)\left(E_2 + E_1\right)} \tag{10}$$

The combined errors of the approximations do not exceed 2-3%, and even this small error is largely canceled out by the initial comparison of the tertiary standards with secondary standards with $\theta < 0.01$.

Calorimeters: Field Use

The rate at which thermal energy is radiated from a nuclear weapon changes rapidly during its detonation. Calorimeters mounted on an airplane are also usually moving directly away from the detonation at a high rate of speed. To interpret the field data, therefore, it is necessary to integrate eq. (2) with H taken as a function of time, with the result

$$E_t = \frac{1}{B} \int_0^{t_f} Ht\, dt - \theta \int_0^{t_f} Edt \tag{11}$$

If the time t_f is taken to be some time after all the energy has been delivered the first integral is equal to the total energy Q. Substituting and rearranging

$$\frac{Q}{B} = E_t + \theta \int_0^{t_f} Edt \tag{12}$$

The solution of the remaining integral in eq. (12) requires numerical integration of the field data. There are several ways of doing this, but the one which follows appears to be the simplest. The decay constant θ can be obtained from the tail of the field curve using

eq. (4), or, with greater ease and probably equal accuracy, the value obtained during the calibration procedure can be used.

(1) Determine on the data curve the time t^* where energy ceased to be received by the calorimeter. For nuclear events near the ground, it is recommended that $10W^{1/2}$ seconds be used for t^*, where W is the yield of the weapon in megatons. For other pulses, t^* should be the point on the curve where the value of θ calculated does not change with time.

(2) Divide the time between zero and t^* into N equal time intervals U. U should be about one second.

(3) Read the deflections at each U. Call the readings $E_1, E_2 \cdots E_t$.

(4) Add $(E_1 + E_2 + \cdots E_t) = \sum E$

(5) Subtract $E_{t/2}$ from $\sum E$ to correct for averaging bias   .

(6) Multiply $\left(\sum E - E_{t/2}\right)$ by $U = E_c$

(7) Multiply E_c by $\theta = \theta E_c$

(8) Add θE_c to the reading, E_t

(9) Multiply $(E_t + \theta E_c)$ by the instrument calibration constant B to get Q, the total energy received prior to time t^*.

A typical curve of field data for two different calorimeters is shown in Fig. 2, and a typical data reduction is shown in the sample problem in the appendix.

The use of the time $10W^{1/2}$ seconds for the end point in reducing the field data from a nuclear detonation is based on the fact that virtually all of the energy of importance from an effects standpoint is received by this time. The remainder of the energy, about 18% (Ref. 3, p. 357) is delivered in a very long time at a low rate where it is usually difficult to read the trace accurately. To obtain the total energy over all time it is best to calculate the results as indicated and divide the answer by 0.82. If this procedure

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is followed, of course, it is important that t^* be as close as possible to $10W^{1/2}$ seconds. It will be noted in ref. 3, Fig. 7.91, that the curve of energy received versus time has not flattened out at this time.

For short nuclear pulses in the lower atmosphere, where $10W^{1/2}$ seconds is less than $0.05/\theta$, it is a satisfactory approximation, for stationary calorimeters, to set Q, the energy delivered prior to $10W^{1/2}$ seconds equal to $BE_t(1 + 0.750t^*)$, where E_t is the calorimeter output at $10W^{1/2}$ seconds. This procedure has an error of less than 5% and is based on the fact that the average voltage between 0 and $10W^{1/2}$ is equal to $0.75\ E_t$ if cooling is neglected

Calorimeters: Decay Constant:

The assumption that the rate of cooling of a calorimeter button is Newtonian is equivalent to the mathematical statement:

$$E_t = E_t \exp(-\theta t) \quad . \tag{13}$$

Where E_t is the output from the calorimeter at the time the irradiance ceases, and E_t is the output at some time t after this. This equation would plot as a straight line on semilogarithmic paper.

To test the validity of this assumption, a brass calorimeter, chosen because this series has the highest decay rate of any of the NRDL field calorimeters, was heated to an output of 3.30 mv and the cooling curves determined, as shown in Fig. 3. The points are the data points and the curves fit three different equations. The curves were not drawn through the points. The straight line represents eq. (13) with $E_t = 3.30$ and $\theta = 0.051$, as derived from the calibration curves.

The data fits the curve to within ±2% for forty seconds, at

which time it begins to deviate. A closer fit can be obtained by
assuming a zero shift during the cooling process, which might result
from a temperature change in the reference junction. An almost exact
fit, within the spread of the data, can be obtained by assuming that
the curve represents the cooling of two structures, one much more
massive than the other. The double structure equation would indicate
that the heat lost from the button is largely absorbed by the
surrounding structure, which has a much larger mass than the button.
The increase in temperature of this structure would reduce the rate
of heat loss from the button. A combination of structure and reference
junction warming probably occurs actually.

Since the Mitchell calibration source does not irradiate the
entire instrument face with the same irradiance that falls on the
button, measurements were also made with a heat lamp, which does.
There was no significant change in the data.

The close fit to a straight line of the experimental points
over a forty second period indicates that the assumption that η is a
constant is valid for thermal pulses as large as 20 MT, even for
calorimeters with the highest losses. Since this value encompasses all
the tests on which NRDL instruments have been used, the assumption has
caused no inaccuracy in the data so far reported.

Calorimeters: Irradiance Measurements:

The rate of change of the output EMF from a calorimeter
during a thermal pulse is, as can be seen from eq. (2) a function of
the irradiance. Rearranging the terms in eq. (2) and integrating,

$$\frac{1}{B} \int_0^t H dt = E + \eta \int_0^t E \, dt \tag{14}$$

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If the output curve of EMF is corrected point by point, in accordance
with eq. 11, a final corrected curve is obtained that is a plot of
eq. (3). Point by point differentiation of the corrected curve will
then give a plot of irradiance versus time.

The output EMF from the calorimeter will, of course, lag
the input energy by the time required for the heat absorbed at the front
face of the button to diffuse through to the point where the thermocouple
is located. It has been shown (ref. 1) that the time for the surface
to which the thermocouple is attached to reach 63% of the front surface
temperature is given by $0.172L^2/K$ where L is the distance in cm from
the front surface to the thermocouple attachment point and K is the
thermal diffusivity ($cm^2 sec^{-1}$) of the button. For OFHC copper buttons
less than 0.3 cm thick, such as those used in the least sensitive
instruments, this lag time is less than 0.02 second and has usually
been neglected.

RADIOMETERS: GENERAL

The NRDL radiometers are of the circular foil type first
described by Gardon (Ref. 4). A circular foil of metal, silver or con-
stantan, is attached to a heat sink at its edges. A differential
thermocouple, constantan-silver for silver foil or constantan-copper for
a constantan foil, measures the temperature rise of the center of the
foil above the heat sink when the foil is exposed to thermal radiation.
Such radiometers can be made simple and rugged and the rather low
sensitivity is an asset for the levels of irradiance for which they are
used.

The heat sink can be water cooled, as in some of the labor-
atory radiometers used for continuous duty monitoring of the output from
high irradiance sources, or have a large heat capacity, as in most field

instruments. Some of the most recent field radiometers, designed
to measure very long thermal pulses are of a water cooled type.
Wherever possible, the radiometers are mounted in the same size case
as the field calorimeters. A pictorial drawing of the radiometers is
shown in Fig. 4.

If the foil is considered to be a thin section through an
infinite cylinder, with heat generated uniformly within its volume,
then an analysis of the heat flow and temperature rise given in ref. 5
applies and

$$\Delta T = \frac{Hr^2}{4KL} - \frac{2H}{rKL} \sum_{n=1} \frac{J_o(o)}{i_n^3 J_1(ri_n)} \exp(-ki_n^2 t) \quad . \tag{15}$$

Where ΔT is the temperature rise at the center of the foil, the i_n are
the positive roots of the Bessel function $J_o(ri_n) = 0$, and r is the
radius, L the thickness, K the thermal conductivity and k the thermal
diffusivity of the foil. The heat is actually absorbed in the front
surface of the foil, of course, but the time required for the rear
surface temperature to reach 99% of the front surface temperature is
less than 200 microseconds for the thickest foils used. This time is
short compared to the total equilibrium time of the foil so that the
assumption of uniform heat generation throughout the volume is valid,
and eq. (15) holds very well.

For equilibrium conditions in a beam of constant irradiance,
the second term of eq. (12) drops out and

$$\frac{\Delta T}{H} = \frac{r^2}{4KL} \quad .$$

The irradiance is then

$$H = \frac{4KL}{r^2 Z} E = E \tag{16}$$

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The term   is the calibration constant for the radiometer, usually given in cal $cm^{-2}sec^{-1}mv^{-1}$ and Z is the conversion factor required to change the temperature rise in ^{o}C in millivolts.

The second term in eq. (15) contains the information on the rate of change in H. The time constant of the instrument, t_c, defined as the time required for the output to change to 63% or (1-1/e) of its final value in response to a step change in irradiance, is equal to that value of t at which the second term in eq. (15) is equal to 37% of the first term. The second term is an infinite series, but by substituting values for i_n taken from a table of Bessel functions it is apparent that members of the series after the first contribute less than 1% to the final value. To evaluate t_c, eq. 15) is rewritten as

$$\Delta T = \frac{Hr^2}{4KL} \left[1 - \frac{8}{r^3 i_1^3 J_1(ri_1)} \exp(-ki_1^2 t) \right] \qquad (17)$$

at t=0, ΔT=0 and $8/r^3 i_1^3 J_1(ri_1)$ = 1. As long as only the first value of i_n need be considered, then

$$\Delta T = \frac{Hr^2}{4KL} \left[1 - \exp(-ki_1^2 t) \right] \qquad (18)$$

The 63% point therefore results when $\exp(-ki_1^2 t_c)$ = 1/e and $ki_1^2 t_c$=1. The first positive root of the Bessel function $Jo(ri_n)$ is 2.405 so that $(ri_1)^2$ = 2.405^2, and t_c = $r^2/5.77k$. (19)

Radiometers: Calibration:

Calibration of a radiometer is accomplished by simply exposing the instrument to a calibrated beam of an irradiance level sufficient to give an output of 2-4 millivolts and observing the output for a few seconds. The beam energy is calibrated in the same

manner as for the calorimeters, using the same tertiary standards. Calibration for field use is usually accomplished at the same time as for the field calorimeters.

Radiometers: Field Use

Field data from a radiometer is usable as read. Allowance must be made for the non-linearity of the thermocouple output if the temperature elevation of the foil center is more than 100°C, or an output of more than 4 millivolts. The time constant of several milliseconds is too long to allow the clear resolution of the first pulse from a nuclear detonation. Radiometers with passive heat sinks (non-water cooled) cannot be used for pulses of more than 60 to 90 seconds, with the shorter value being the limit at high irradiances near the rating of the instrument.

SOURCES: GENERAL

The thermal radiation from a nuclear detonation in the atmosphere at low altitude has a spectral distribution similar to the sun; that is, it radiates approximately like a black body at 6000°K at the peak of the second pulse. As a rule of thumb, the total energy in cal/cm^2 received at a point distant in space from the detonation is $(W \times 10^3)/D^2$ where W is the weapon yield in megatons and D the distance in statute miles. This value will be reduced by the intervening atmosphere but forms a convenient upper limit for estimating purposes. It is also stated as one cal/cm^2 per kiloton at one mile.

The numerical value of the maximum irradiance levels received from a nuclear detonation is higher than the numerical value of the

total energy received at the same place for small weapons, becomes equal for weapons of about 100 kt yield, and is smaller for large weapons. Dimensionally, of course, irradiance and total energy are not the same, but for a detonation of 100 kt yield, a receiver which records 10 cal/cm^2 total will have seen a maximum irradiance near 10 $cal/cm^2/sec$. This maximum value is given in ref. 3 as approximately equal to $4(W \times 10^3)^{1/2} cal \, cm^{-2} sec^{-1}$.

An irradiance level of one $cal/cm^2/sec$, which is at the lower limit of interest from an effects standpoint is an extremely high level one for most purposes. It is about 50 times full noon sunlight. A typical NBS 100w standard lamp will, at a normal working distance of one meter, provide an irradiance level of 10^{-4} to 10^{-3} $cal/cm^2/sec$. Laboratory sources to simulate the radiant power from a nuclear detonation must, therefore, be of large size with large electrical power inputs.

Sources: Specific: Carbon Arc

The spectral distribution of the thermal energy from a nuclear detonation is most conveniently simulated by a focussed carbon arc source, using carbons cored with various salts to increase the output in the visible region of the spectrum. NRDL has three such sources, one a modified Navy 36" searchlight and two modified movie projectors. All three are of the high current type and dissipate half or more of the input electrical energy in an external ballast resistor. The searchlight beam is refocussed and provides an irradiance level of 90 $cal/cm^2/sec$ into a 3/8" diameter spot, from a total electrical input of 20 kw. One of the other sources, the Mitchell background projector, consumes up to 25 kw and is capable of a maximum irradiance

of 25 cal/cm^2/sec into a $3/4$" diameter spot, while the third source, the
Brenkert projector, will provide nearly 7 cal/cm^2/sec into a one inch
diameter spot, with a total power consumption of 8500 watts. The arc
voltage is 40 volts dc for the Brenkert and 60-70 volts dc for the other
two sources. All of the beams are converging, with the searchlight
having an f-ratio of about 0.4, the Mitchell 0.6 and the Brenkert 7.0.

Carbon arc sources are inherently rather unstable. Extensive
work with the Brenkert source gave a variation of ±3% that could not be
calibrated out or otherwise eliminated (Ref. 5). The Mitchell source
is no better and the searchlight worse. Furthermore, the irradiance is
not completely uniform across the spot. The spot sizes listed above
are for a maximum variation of -10% from the highest value of irradiance.
Both the Mitchell and searchlight sources are equipped with high speed
shutters capable of giving exposure times of a few milliseconds, and the
Mitchell is also equipped with a mechanism to generate a pulse with the
same time variation as the nuclear weapon pulse. Photographs of the
sources are shown in Figs. 5, 6 and 7.

Sources: Specific: Tungsten:

The recent commercial availability of small high wattage tungsten
filament lamps has made it possible to construct high irradiance tungsten
filament sources of relatively large areas. NRDL has constructed during
Fiscal 1964 a 8500 watt source built around 13 five hundred watt General
Electric quartzline lamps. These lamps operate on a tungsten-iodine
cycle which depends upon the reversible reaction between tungsten and
iodine at two different temperatures to minimize the effect of filament
evaporation. The lamps have a fused quartz envelope that operates at
600°C and, at rated voltage, maintain the filament at 2750°C. They are

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small and all thirteen are located in a volume only 3 inches high and 7/8 inch deep. Active filament width is about 2 3/4 inches. The housing is constructed of aluminum, brass, ceramic, steel and fused quartz, and all wiring is done with teflon coated wires to enable the source to be used without forced air cooling, although a blower is incorporated for normal use. A maximum irradiance of 1C cal/cm^2/sec is available immediately outside the window and falls off slowly with distance. Spot distribution is uniform to ±5% over an area a little over an inch in diameter just outside the window and increases to over 3 inches in diameter at the 3 cal/cm^2/sec level. Each individual lamp can be connected separately, but at present the 13 lamps are connected in two banks, one of 7 and of 6 lamps, with the 7 lamp bank controlled by a variable transformer. Appropriate relays and timing equipment are provided for the source operation. Details are given in Fig. 8 and a photograph in Fig. 9.

Extensive experience has shown that for certain operations the spectral distribution of the radiant energy is of minor importance. NRDL instruments are essentially black over the spectral region to which the windows are transparent (0.2 to 3.5 microns for fused quartz). Charring or ignition of organic materials is also not usually a strong function of spectral distribution. The tungsten source is much more stable and reproducible than the carbon arc sources, and for these purposes where its lower effective radiating temperature is not a handicap is much easier to use. The relatively large uniform area is also an asset of considerable importance for many studies.

TECHNIQUES: GENERAL

The design of thermal instruments can be described mathematically, but construction is an art requiring painstaking care. For example, the theory of the radiometers assumes a single sharp line junction between foil and heat sink at the temperature of the sink. To even approach this assumption in practice involves machining pure metals to an exact contour and precisely locating foils thinner than a human hair in the machined spaces. Most of the work is done under microscopes with jewelers lathes and drill presses. Because of inevitable variations in foils, buttons, wires and skills - not to mention luck - the instruments vary from each other and from the design. Metal foils, particularly, are almost impossible to obtain perfectly flat. They invariably contain ripple marks from the manufacturing or mill rollers.

During Fiscal 1964 modifications were made on the radiometers to increase their reliability and the construction started on a calorimeter sealed in an evacuated glass envelope. Schematic drawings of these instruments are shown in various illustrations which are, to a considerable extent, self-explaining. Some of the fine details are discussed below, along with some of the concepts and considerations incorporated in the NRDL instruments.

Techniques - Temperature Sensors:

All of the field instruments and most other instruments have depended upon thermocouples of one type or another. The calorimeters used so far have had copper constantan couples, while the radiometers have usually used silver constantan. The vacuum calorimeter under design study is expected to use a chromel-alumel thermocouple.

All thermocouples produce an emf whose magnitude depends upon the temperature difference between points located in different junctions of the wires, and upon the absolute temperature. Ideally, there should be only two junctions between wires, with one at the point whose temperature is desired, and the other at a fixed, known temperature. The junction between any two metals is, however, to some extent a thermocouple, and since an indicator of some type must be used, with electrical connections to it, the ideal case is never achieved. One of the principal virtues of copper-constantan couples is that the measuring indicator can be on the copper side, and copper extension leads can be used. Copper-constantan forms a stable sensor for temperatures below 500°C and is widely used but is rather non-linear over most of the range. Silver constantan forms a couple almost identical with copper canstantan. Chromel alumel is more linear with temperature than either of the others.

Techniques - Calorimeters:

A thermocouple measures the temperature near the last point at which the two wires touch. To insure that this point was within the body of the calorimeter button, the wires are inserted into two separate holes, as shown in Fig. 1, and peened in place with a small punch. This method was adopted after attempts to soft solder, silver solder and weld the wires in place had proved to be unsatisfactory. Soft solder would not stand the maximum temperature rise, and both soft and silver soldering added mass to the button. Furthermore, the precise location of the junction was difficult to determine. Spot welding of small pure copper wires to bulk copper is difficult and unreliable. Peening proved to be a very reliable method, after the problem of

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drilling 0.006 inch diameter holes in OFHC copper had been solved.

The calorimeter button was mounted, in the field instruments, on small L shaped steel pins, with the short leg which touched the button sharpened. The pins were under tension so that the pointed ends dug into the button and held it. This method of mounting required a button at least 0.02 inch thick, to provide a contact area for the pins and to support the pressure. This thickness gave a sensitivity of about one $cal/cm^2/mv$, which was too low for some of the desired measurements, but the loss factor of 5% per second was the maximum considered tolerable for accurate data gathering.

Air conduction and convection account for about three quarters of the losses from the calorimeter button. Reducing the air pressure to 10^{-6} Torr essentially eliminates this loss, and much thinner - and therefore more sensitive - buttons can be used than those described above before the loss factor becomes excessively large. A schematic drawing of a prototype vacuum calorimeter built this past year is shown in Fig. 10. The method of mounting the button was changed so that the strain of the mounting on the button would be tension rather than compression, and also to reduce the loss by conduction through the supports. The button is supported on the chromel-alumel thermocouple wires and one neutral chromel wire. All the wires are 0.010 inch diamter, peened into small holes in the button. This thermocouple combination was chosen because of its greater linearity, physical strength, and lower thermal conductivity than copper-constantan. The thermocouple leads are led through the envelope to an external reference junction. The calorimeter has a fused quartz window, with a glass body graded back to a glass-kovar header, designed to fit a standard octal socket. Considerable attention has been paid to the interior geometry of the button support to minimize the reflection of radiation

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onto the button from the back. The design of this instrument has not been finalized.

Techniques: Radiometers:

The construction of accurate and reliable radiometers has been a much more difficult problem than the construction of the calorimeters. The primary reliance upon calorimeters to determine field data is largely due to the difficulties in constructing and maintaining radiometers, which are, in principle, considerably easier to use. For some time in the later field tests they were used as zero time markers only. During the past year, however, new series has been built and many of the previous difficulties seem to have been overcome.

The mathematical description of a radiometer, given before is not extremely complicated. However, the mathematical description depends upon several assumptions: (1) that the temperature sensor is at the center of the foil and does not itself affect the temperature rise; (2) that the edge of the foil is at the same temperature all the way around and that this temperature does not change during exposure; (3) that the foil contacts the heat sink at a single sharp corner; (4) that the second temperature wire is measuring the temperature at the edge of the foil; and (5) that the energy is absorbed uniformly across the entire face of the foil. Despite considerable care and skill, none of these assumptions is met completely in practice, although 5 is approached.

Figure 11 includes sketches taken from some of the working drawings of various parts of the radiometers built during late 1963. Figure 11 shows the finished radiometers. The precise shapes of the parts were usually determined by the requirements of heat transfer - either from the foil or from the cooling water. The larger instrument,

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RLSW, was designed to measure the radiation from a fire composed of burning liquid hydrogen and liquid oxygen, with the fire engulfing the instrument at times. A very large capacity for cooling water was therefore provided, with the signal cable brought out in the water line. The duration of the input was expected to be up to several minutes. The other instruments were for more modest inputs.

Techniques: Radiometers: Foil Mounting:

Attaching the foil to the heat sink has been the most difficult problem to solve in the construction of radiometers. The original attempt was to soft solder a silver foil to a copper sink. This technique failed, with the radiometers showing considerable zero drift. This was traced to the formation of a filet of comparatively low conductivity solder at the junction of the foil and the sink, with a resultant wandering of the temperature at the foil edge. Soft soldering has been resurrected in the latest high sensitivity radiometers, with the heat sink carefully machined to a contour as shown in the drawings (Figs. 12 and 13), the foil formed against it before soldering, and the solder kept away from the edge. The soldering is performed with the foil under tension so that mechanical forces hold the foil and the heat sink edge in good thermal contact.

The foils used on most of the instruments built during the 1950's were "stitched" to the heat sink by a series of overlapping spot welds. The finished heads were tested before assembling and those that drifted were rejected. There were a large number of failures, for it is very difficult to spot weld materials of such high electrical conductivity as copper and silver. The instruments also had a rather high failure rate in the field exhibiting drift

and changed output. These failures were primarily due to corrosion or mechanical failure at the foil edge contact or separation of the center contact from the foil. The center contact was spot welded to the foil and the constantan-silver foil contact was not always strong. There was no way of testing this joint without destroying it. These early radiometers are shown in Fig. 14. A few radiometers were built with the foil pressed against the heat sink with heavy spring pressure (Fig. 4). These mountings worked quite well but were mechanically rather complex.

The seven mil (.007") foils used in the RLSW series of instruments were spun into the heat sink. An accurately cut foil was placed in the center of the machined sink and the raised portion of the sink was rolled smoothly over the foil edge by pressing a burnishing tool against it while it was spinning in a lathe. This joint was extremely strong and made excellent thermal contact between the two elements. The five mil (.005") constantan, center wire was staked into a six mil hole with a fine hollow punch and anvil. When properly made, the joint was stronger than the wire.

The foil used in the RFS series was one mil (.001) (Fig. 13) thick and a two mil (.002") wire was silver soldered to the back. The silver soldering was accomplished with a micro hydrogen-oxygen torch and the amount of solder used was extremely small. The foil was held flat above the torch in a jig and the prefluxed wire was touched to its other side. A couple of filings from a small silver solder wire were stuck to the wire by the flux. When everything was adjusted correctly the loss of heat by conduction from the foil was sufficient to melt the solder (low-temperature type, melting point about 600°C) when it contacted the silver. A shutter was incorporated above the flame of the torch to enable the heat to be shut off immediately after the solder flowed. The operation was watched and guided through a 20 power

binocular microscope. This foil was soft soldered into the heat sink.

Techniques: Metal Forming:

The thermal conductivity and diffusivity of metals is a strong function of their purity and mechanical state. The sensing elements in the NRDL instruments use metals, usually copper and silver, of the highest commercial purity. Unfortunately, such metals are difficult to machine. They are soft and "sticky," adhering to tools and causing chattering, galling and tool breakage. Successful machining depends upon sharp tools, small cuts, slow feeds, and proper lubrication. The operator must be very patient and develop a feel for his tools. The techniques are not within the field of general machine shop practice, and even a very skilled machinist must be given a considerable period of time to develop the additional skills necessary for micromachining. Because of the variation between people, different operators develop their own methods, and what works for one person will not necessarily work without modification for another. As with other forms of art requiring close coordination between hand and eye, skills in micro-machining are attained only with practice.

Techniques: Coatings for Receiving Surfaces:

The surfaces exposed to the incident thermal energy by both the radiometers and calorimeters are flat, and depend upon a coating to absorb the energy. After a considerable amount of study the coating decided upon was electrolytically deposited platinum black and, with a few exceptions, this coating has been used on the calorimeters and radiometers for all the field operations.

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Platinum black is, basically, a very poor platinum plating. It has been used for more than 60 years as a non-polarizing coating for electrodes in electrochemistry, and for a number of years as a coating for receivers in the measurement of radiant energy. Properly prepared, it is an almost perfectly black coating which is stable in air to temperatures above $500^{\circ}C$ but which is quite fragile to the touch. Rubbing the surface with a tissue removes a fine black powder and leaves a diffuse grey coating on the substrate. Data taken at NRDL (Ref. 6) indicates that it radiates as an almost perfect diffuse radiator with no significant deviation from the cosine law, at least at elevated temperatures.

Platinum black, as prepared at NRDL, is electroplated from an aqueous solution of chloroplatinic acid, H_2PtCl_6, 30 g/liter with 0.3g/liter of lead acetate, $PbAc_2$ added. The material to be blackened is made by the cathode (negative) terminal with a platinum anode. The distance from the anode to all parts of the cathode should be approximately the same. Current densities are in the range 0.02 to 0.1 amperes per square centimeter. The actual values used are determined by the amount of bubbling which occurs at the cathode surface. The bubbling should be free and abundant, but the bubbles should not be large, since large bubbles may mask portions of the surface from the electric field, and their bursting may knock off portions of the coating. Gentle movement of the piece during coating helps in removing the bubbles and also tends to even out differences in deposition rate due to variations in the anode cathode distance.

The reaction has a peculiar, and, at least by the author of this report, not very well understood tendency to reverse at times, and a nearly complete coating can be neatly and rapidly stripped off in an attempt to make it a little better. The reversal usually occurs if the current has been interrupted with both electrodes inthe solution, or if the electrodes are immersed and the power turned on. Consequently,

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the voltage should be applied to the system with one of the electrodes out of the solution, and the circuit completed by lowering the electrode into the plating bath. The reversal may frequently be re-reversed by momentarily increasing the voltage across the bath by 50% or so. A relatively high voltage (up to 25 volts) applied to the bath through a dropping resistor appears to be more effective in minimizing difficulties than supplying the same amount of current from a constant voltage source. The voltage across the bath is usually less than 10 volts.

The substrate materials to be coated must be immaculately clean. The importance of this cannot be overstressed. The substrates used here were first cleaned of all oxides, greases, dirt and so forth using whatever combination of acids, detergents and organic solvents that were effective and then the surfaces were mechanically cleaned using an ink eraser in an electric eraser holder such as is used by draftsmen. The copper discs were usually cleaned in strong hydrochloric acid and rinsed briefly in nitric acid before buffing. A final dip in clean acetone and a rinse in distilled water was frequently desirable.

The coated button was removed from the plating bath with the voltage still applied. After a brief inspection to determine the appearance of the coating, it was returned to the bath unless the coating was satisfactory, but was not permitted to dry. When the coating was finally acceptable, it was rinsed extensively with running hot water and then with distilled water. The buttons were usually air dried, sometimes with warm (not hot) air from a blower, but they were not exposed to temperatures above 100°C until they were completely dry.

With some experience, visual inspection of platinum black coatings immediately after drying provides a good indication of their absorptive properties. A good coating appears very black and diffuse, especially when viewed under a strong light. When compared with most

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other blacks, it looks like a hole. The absorptance is very close to one.

Aside from its fragility to touch, about the only drawback to platinum black as a coating is its difficulty of application. It can only be applied to metals that are inert to the plating solution, such as gold and silver and copper, the plating solution will rapidly attack constantan, although alumel and chromel wires stand up well.

Some of the new black paints also have absorptances near one, and a few of the radiometers, particularly the RLSW series, were painted with a very thin coating of Minnesota Mining and Manufacturing Company's 3M/Velvet Black. Although the mass added to the foil is greater with the paint than the platinum black, the paint was satisfactory for the rather thick foils of this radiometer series. This paint is a very diffuse material capable of standing elevated temperatures after proper curing, i.e., air dried first for several hours, followed by heating to about 100°C.

Techniques: Field of View:

As is shown in the drawings, most of the field instruments could see a 90° full angle field of view. The RLSW geometric field of view was over 160°, but was probably limited to somewhat less than that by reflection at the fused quartz window. Figure 15 is a drawing of a standard instrument with a domed window, built to approach 180° field of view (2π solid angle). This attempt was not too successful since the dome acted like a lens, focusing the irradiant energy to some extent. Because of the almost perfect diffuseness of the platinum black surface cosine corrections could be applied to irradiance received off the center of the line of sight with very little error.

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The stepped apertures on the standard instruments were to reduce reflection from the metal onto the button.

Techniques: Recording: Field Recording

Almost of the data taken by NRDL and others using NRDL calorimeters and radiometers have been recorded on oscillographic machines using photographic paper. The NRDL data was taken on Heiland recorders, using low impedance galvanometers with a frequency response flat to 60 cycles when properly damped. This represents time response of about 4 milliseconds, sufficient to resolve the second peak of most nuclear detonations, but not the first.

Photographic galvanometric recorders like the Heiland are very practical for field recording even now. They are light, can be made rugged and durable, and compress more recording channels into a given space than any other form of recorder. Their power demand is relatively low and can be provided from batteries. They suffer from relatively limited frequency response or sensitivity - one can only be obtained at the expense of the other. Direct writing oscillographs are not usually acceptable for field work at unmanned stations, although they are excellent for manned stations with line power and shelter from the elements.

The thermocouples of the radiometers and calorimeters have an internal impedance of from five to one hundred ohms, practically pure resistance, and an output in the millivolt range. This output is too low for direct input to presently available tape recorders and pre-amplifiers must be used. The requirements of flat frequency response from dc to one hundred cycles/sec with an equivalent input noise of ten microvolts peak to peak over this range is a severe one, and

commercial amplifiers do not seem to meet these requirements. However, transistorized operational ampfliers, battery operated, and with appropriate feedback networks will work, and these amplifiers are commercially available, although the external networks have to be added and the units packaged.

As part of the vacuum calorimeter design, small portable self-contained amplifier-recorder combinations are being studied, and a prototype compact light weight unit is to be built within Fiscal Year 1965.

Techniques: Recording: Calorimeter Calibration

During the calibration procedure, one calorimeter at a time is exposed to a known level of irradiance for known periods of time. Both the level of irradiance and the duration of the time may be controlled over wide limits to give the desired output voltage from the instrument. The recorders used for calibration are therefore chosen for sensitivity and accuracy, with time response only of secondary interest.

The initial work done at NRDL used strip chart potentiometric recorders with a maximum sensitivity of one-half or one millivolt full scale and a time response of one-half second (Brown recorders from Minneapolis-Honeywell Co.). Reading the charts from these instruments was a tedious task, and when several hundred instruments had to be calibrated sometimes months were required to reduce the data. During the preparation for the Plumbbob series of tests in 1957, a digital coder was attached to a Brown recorder and the data taken out through appropriate relay matrices and IBM card punches on IBM cards in form suitable for machine computation. The work of months was reduced in

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this fashion to a few hours, and the data were more accurate.

This system was dismantled during the nuclear test moratorium preceding 1962. When calibrations were resumed prior to the _Dominic_ series, a new technique was worked out, the mathematics of which were described previously under Calorimeters: Calibrations;. This system is nearly as simple as the IBM readout and considerably more flexible. It can be used with either the carbon arc sources or the tungsten source.

The primary difficulty with the use of strip chart recorders is that the data is produced in analog form, while calculations can only be made upon digital data. The process of reducing the analog data to digital data was the most time consuming step of the early calibration procedure. It was also relatively inaccurate, since everything had to be read off a paper chart.

Within the past five or six years several instruments which measure voltage and present their information directly in digital form have become available. These digital voltmeters have outputs which can be recorded upon digital printers, making them very convenient substitutes for other types of recorders when digital data are required. The three different basic types, with their different characteristics, will be described briefly, with comments as to their applicability to calorimeter calibration. A sample calibration is also presented in Appendix B showing the different approach sometimes dictated by the limitations of the instruments.

The first digital voltmeters were essentially mechanized potentiometers. This type of voltmeter is still used and is capable of the very highest accuracy. The input voltage is compared with an internally generated voltage, and the internal voltage is changed through a logical sequence by means of mechanical stepping switches

until a comparator circuit indicates that the difference between the internal and external voltages is zero. The process is then stopped at this position, and the voltage is indicated upon a numerical readout. However, this type is rather slow, requiring up to five seconds or more to balance, and will not give any reading at all on a rapidly changing voltage, thus making it unsuitable for calibration purposes. Useable digital voltmeters of essentially the same type using all solid state switches have become available recently, however, with balance times in the ten millisecond range and with stability and accuracy comparable to the mechanical type.

A simpler and less accurate, although of adequate accuracy for calorimeter calibrations, voltmeter is the ramp type. These are also comparison instruments, but the internal voltage starts at zero and rises linearly with time until it equals the applied voltage. The time from zero to equality is recorded by a precision oscillator-counter combination and presented as a digital display which is calibrated in volts. A reading will be obtained on varying voltages as well as steady ones. Because of heavy filtering against stray noise most ramp type voltmeters have response times of one to two seconds. They are also not very accurate for large step voltage changes, taking two or three readings to settle down to the final value. To use this type for calibration purposes requires an accurate knowledge of the exposure time. These are the least expensive digital voltmeters. Both the ramp and potentiometer type voltmeters need preamplifiers to extend their range into the low microvolt region required.

The units presently in use at NRDL are of a third type, integrating digital voltmeters. These instruments convert the incoming voltage to a frequency, with the frequency linearly related to the voltage. (For one of the voltmeters, a full scale input voltage of 0.1 volt causes an output of 100,000 cps, so that 0.025 volts would

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result in a 25,000 cps output). The frequency changes in accordance
with the input voltage with a lag of not more than one cycle of the
output frequency, or about 10 microseconds for a full scale change.
This frequency is counted on a digital counter for a precise period
of time called the gate time, 0.01, or 0.1 or 1 second for the units
in use, and the results displayed in digital form. The output is the
integral of the input voltage over the gate time, or

$$E_r = \int_0^{t=G} E_i \, dt$$

where E_r is the indicated voltage, G is the gate time in seconds, and
E_i is the instantaneous value of the input voltage. The integrated
value of noise over long periods is zero, so that the instrument
inherently discriminates against noise, and filtering is not necessary.
The gate times are usually controlled to one part in 10^5 or so, and
the best voltmeters of this type are intermediate in accuracy between
the other two. All three types are generally better than 0.1% of full
scale in accuracy.

Calorimeter Field Data Reduction

Sample Problem

A four MT thermal pulse was simulated by the NRDL Mitchell
source. Fig. 2 shows the output curves from two successive pulses
as measured by NRDL field calorimeters of different sensitivities
and losses. (The curves do not represent the shape of the pulse the
calorimeters saw, only the EMF of the calorimeter output). Each curve
was read at each point marked. Since the simulated yield was given as
four MT, $10W^{1/2}=t^*=20$ seconds. The color designation on the instruments
represents the different sensitivity ranges, with the red instrument less
sensitive than the brass.

The Mitchell source is actually adding energy to the calorimeter
for the entire period of $10W^{1/2}$ seconds. Note that the output starts
to decrease even before the input drops to zero, and, because of the
different decay constants, that the instruments peak at different times.

APPENDIX A

Time, U, seconds	Reading E, mv, for Red 300	Reading E, mv, for Brass 203
1	.03	.26
2	.32	2.44
3	.81	5.28
4	1.11	6.71
5	1.29	7.39
6	1.40	7.70
7	1.48	7.75
8	1.54	7.62
9	1.55	7.38
10	1.57	7.09
11	1.57	6.76
12	1.55	6.42
13	1.54	6.08
14	1.53	5.78
15	1.53	5.48
16	1.50	5.21
17	1.48	4.95
18	1.49	4.70
19	1.47	4.46
20	1.45	4.23
$\sum E$	26.21	113.69

Then

Step (4) $\sum E$ = 26.21 Red 300 E_t=1.45 mv

$\sum E$ = 113.69 Brass 203 E_t=4.23 mv

Step (5) $\sum E - E_t/2$ = 26.21 - .72 = 25.49 mv

$\sum E - E_t/2$ = 113.69 - 2.11 = 111.78 mv

Step (6) $\left(\sum E - E_t/2\right) \times U$ = 25.49 x 1 = 25.49 mv

$\left(\sum E - E_t/2\right) \times U$ = 111.78 x 1 = 111.78 mv

Step(7) ∂ = 0.011 for red instruments

∂ = 0.051 for brass instruments

∂E_c = (.011)(25.49) = .281

∂E_c = (.051)(111.78) = 5.70

Step (8 and 9) B = 6.34 cal $cm^{-2}mv^{-1}$ for red 300

B = 1.08 cal $cm^{-2}mv^{-1}$ for brass 203

$(E_t+\partial E_c)B$ = (1.45 + .28)(6.34) = 10.9 cal cm^{-2}

$(E_t+E_c)B$ = (4.23 + 5.70)(1.08) = 10.7 cal cm^{-2}

The agreement is well within the reproducibility of the Mitchell carbon arc source used.

APPENDIX B
Calorimeter Calibration Using Digital Voltmeters

Sample Problem

To illustrate the actual calibration process, a brass calorimeter (nominal sensitivity about one $cal/cm^2/mv$) was exposed to the tungsten source for 4.0 seconds at an irradiance level of one $cal/cm^2/sec$. The data were recorded on two different sets of instruments, and a slightly edited copy of the raw data is shown below. The data tapes from the digital printers are three inches wide, and the last figure to the right in each case is a decimal point indicator, not a significant figure. The next to the last figure to the right on each set of data represents ten microvolts. The negative sign indicates that the high terminal of the voltmeter was connected to the negative thermocouple lead.

Combination one was a ramp type voltmeter with a maximum sensitivity of one millivolt (Hewlett-Packard type 405AR). To increase the sensitivity, a Hewlett-Packard 412A vacuum tube voltmeter was used as a gain of 100 preamplifier. The printer was a Hewlett-Packard 560A. The second combination was a Dymec 2401A integrating digital voltmeter with a Hewlett Packard 562A printer. Because of the slow time response of the ramp type voltmeter discussed before, combination one printed out at one second intervals. Combination two, with the voltmeter set on a 0.1 second gate time, printed twice a second. The editing of the data consisted merely of removing some of the extra numbers recorded before the lamp was turned on. The tapes read from the bottom up, with the first reading representing the calorimeter output before the lamp was turned on. It was not quite zero, indicating that the button was about one degree C above ambient. It had been pre-heated to test the system, and had not quite cooled.

Combination 1	Combination 2
	tymec 2401A voltmeter
-hp- 412A voltmeter	-hp- 562A printer
-hp- 405AR voltmeter	
-hp- 560A printer	

Combination 1	Combination 2
0 0 1 - 3	- 0 0 1 0 7 5
0 6 4 - 3	- 0 0 1 1 0 5
0 6 8 - 3	- 0 0 1 1 2 5
0 7 1 - 3	- 0 0 1 1 6 5
0 7 4 - 3	- 0 0 1 1 8 5
0 7 8 - 3	- 0 0 1 2 1 5
0 8 2 - 3	- 0 0 1 2 4 5
0 8 5 - 3	- 0 0 1 2 7 5
0 9 0 - 3	- 0 0 1 3 0 5
0 9 5 - 3	- 0 0 1 3 4 5
0 9 9 - 3	- 0 0 1 3 8 5
1 0 5 - 3	- 0 0 1 4 1 5
1 1 0 - 3	- 0 0 1 4 5 5
1 1 6 - 3	- 0 0 1 4 9 5
1 2 2 - 3	- 0 0 1 5 3 5
1 2 8 - 3	- 0 0 1 5 7 5
1 3 4 - 3	- 0 0 1 6 1 5
1 4 2 - 3	- 0 0 1 6 5 5
1 5 0 - 3	- 0 0 1 7 0 5
1 5 8 - 3	- 0 0 1 7 4 5
1 6 7 - 3	- 0 0 1 7 9 5
1 7 6 - 3	- 0 0 1 8 4 5
1 8 6 - 3	- 0 0 1 8 9 5
1 9 6 - 3	- 0 0 1 9 3 5
2 0 7 - 3	- 0 0 1 9 9 5
2 1 8 - 3	- 0 0 2 0 4 5
2 3 0 - 3	- 0 0 2 1 0 5
2 4 3 - 3	- 0 0 2 1 5 5
2 5 8 - 3	- 0 0 2 2 2 5
2 7 2 - 3	- 0 0 2 2 8 5
2 8 9 - 3	- 0 0 2 3 5 5
3 0 6 - 3	- 0 0 2 4 1 5
3 2 4 - 3	- 0 0 2 4 8 5
3 4 2 - 3	- 0 0 2 5 5 5
3 3 1 - 3	- 0 0 2 6 2 5
2 4 5 - 3	. 0 0 2 6 9 5
1 5 5 - 3	- 0 0 2 7 8 5
0 6 3 - 2	- 0 0 2 8 5 5
0 0 4 - 3	- 0 0 2 9 3 5
	- 0 0 3 0 3 5
	- 0 0 3 1 1 5
	- 0 0 3 2 0 5
	- 0 0 3 3 0 5
	- 0 0 3 3 8 5
	- 0 0 3 4 5 5
	- 0 0 3 4 2 5
	- 0 0 3 0 0 5
	- 0 0 2 5 6 5
	- 0 0 2 1 2 5
	- 0 0 1 6 7 5
	- 0 0 1 2 1 5
	- 0 0 0 7 6 5
	- 0 0 0 2 9 5
	- 0 0 0 0 4 5

The exposure was for 3.8 seconds. Combination one did not reach
its peak reading for five seconds after the start of the rise because of
the instrument delay. The decay was slow enough so that the voltmeter
was following quite closely. The first step is to find the calorimeter
decay: From eq. (4)

$$\ln\frac{E_1}{E_2} = \theta(t_2 - t_1) \tag{4}$$

The value 306-3 after the peak value may be used for E_1 (this is 3.06 mv)
and if $t_2 - t_1$ is chosen to be 10 seconds, then E_2 is 1.76 mv. So

$$\ln\frac{3.06}{1.76} = \ln 1.74 = .555 = 10\theta, \text{so that}$$

$\theta = .055$, or a 5.5% per second loss rate. This number is then substituted
into eq. (7), with the highest value of E recorded. The time t is the
exposure time, known to be 3.8 seconds, and Q = Ht where H is known to be
one cal/cm^2/sec.

$$\frac{Q}{E}(1-\theta^{t/2}) = B \tag{7}$$

$$\frac{3.8}{3.42}\left(1 - \frac{(.055)^{3.8}}{2}\right) = B = 0.99 \text{ cal/cm}^2/\text{mv}$$

This value is subject to an unknown error of as high as one θ, or 5%,
because it is not known that the voltmeter actually sampled right at the
peak of the curve. Because of the slow response time, it does not help
to read the output at closer intervals. This error is reduced by taking
several reading and averaging them. The slow decay curve enables the
voltmeter to follow, and θ is not subject to the same error.

Exactly the same procedure may be followed with combination 2:
with the result that θ equals .056 and B = 0.98 cal/cm^2/mv. The voltmeter
was gated so that it read in the first 0.1 second after the irradiance

ceased, and the peak value of 3.45 mv is known within less than 1% because of the rapid response. Combination 1 was about 1% off in the example.

With the rapid response of combination 2, it is not necessary to expose for a closely known time. The calibration constant may be determined from the rate of rise of the output in a known irradiance. The procedure is to set up the calorimeter, turn on the voltmeter to establish a zero, turn on the lamp or open the shutter, expose until the output is 3-5 mv, shut off the lamp (or close the shutter) and obseve the decay. The voltmeter is gated at accurately known intervals for accurately known times during this period. The first reading on the rise is ignored, for it is not known during what portion of the preceding interval the calorimeter was being irradiated. To illustrate: The second reading after zero, from the data sheet for combination two, is -000765 or 0.76 mv. After 1.00 seconds (print rate is two/second) the reading is -001675 or 1.67 mv. This is a change of 0.91 mv in one second. The average reading during this time was (1.67 + .76)/2 or 1.215 mv (1.21 mv may be read off the tape at 5 seconds and is equally accurate since digital voltmeters have an unavoidable jitter of +1 in the last place). With a decay constant of 0.056, the final corrected reading is 1.02 mv/cal/cm^2. The overall calibration constant, over the $75^{\circ}C$ temperature rise is the highest reading before the peak (the peak reading is not used in this determination, for the exact point at which the heat was turned off is not known except that it is between the highest reading and the one preceding it) minus the first valid reading plus the energy lost during this period of exposure divided by the time between readings. From the data curve

$$(3.42-0.76) + .35 \rfloor /3 = 1.00 \ cal/cm^2/mv$$

The overall calibration constant, for this instrument, over the entire temperature range is within about 1% of 0.99 cal/cm^2/sec, on the basis of the calculations here. The variations in the last series of calculations on the slope are partially due to the actual non-linearity of the thermocouple, where a one degree change at 100°C represents more output than a similar change at 25°C, and partially due to the unavoidable jitter in the lamp and recording machines. It is because of these variations that the overall accuracy of the calorimeters is usually quoted as ±5%.

APPENDIX C

The sensitivities of some of the NRDL instruments are listed below, together with time constants where these are appropriate. The absolute maximum design output is 10 millivolts, with a desired maximum output of 4 millivolts (or an absolute sensor temperature rise of 250°C and a desired rise of 100°C or less).

Field calorimeters	Sensitivity	decay constant θ
Brass series:	1.10 cal cm^{-2}mv^{-1}	.051
White series:	1.45 cal cm^{-2}mv^{-1}	.036
Black series:	2.90 cal cm^{-2}mv^{-1}	.022
Red series:	6.50 cal cm^{-2}mv^{-1}	.011

Prototype vacuum calorimeter		
Mod I	0.3 cal cm^{-2}mv^{-1}	

		time constant
Field radiometers		
Rd 10-series	2 cal cm^{-2}sec^{-1}mv^{-1}	3-4 ms
Rd 50	10 cal cm^{-2}sec^{-1}mv^{-1}	3-4 ms

Special		
RLSW	15 cal cm^{-2}sec^{-1}mv^{-1}	15 ms
RFS	1.5 cal cm^{-2}sec^{-1}mv^{-1}	15 ms

All the calorimeters of a given series have the same calibration within about 10%, that is, all brass series calorimeters will have calibration constants between 1.00 and 1.20 cal cm^{-2}mv^{-1}. Radiometers vary by a factor of 2 from nominal, with an RD-50 series instrument being any place between 5 and 20 cal cm^{-2}sec^{-1}mv^{-1}. The calibration factor will not change with use unless the maximum ratings are exceeded.
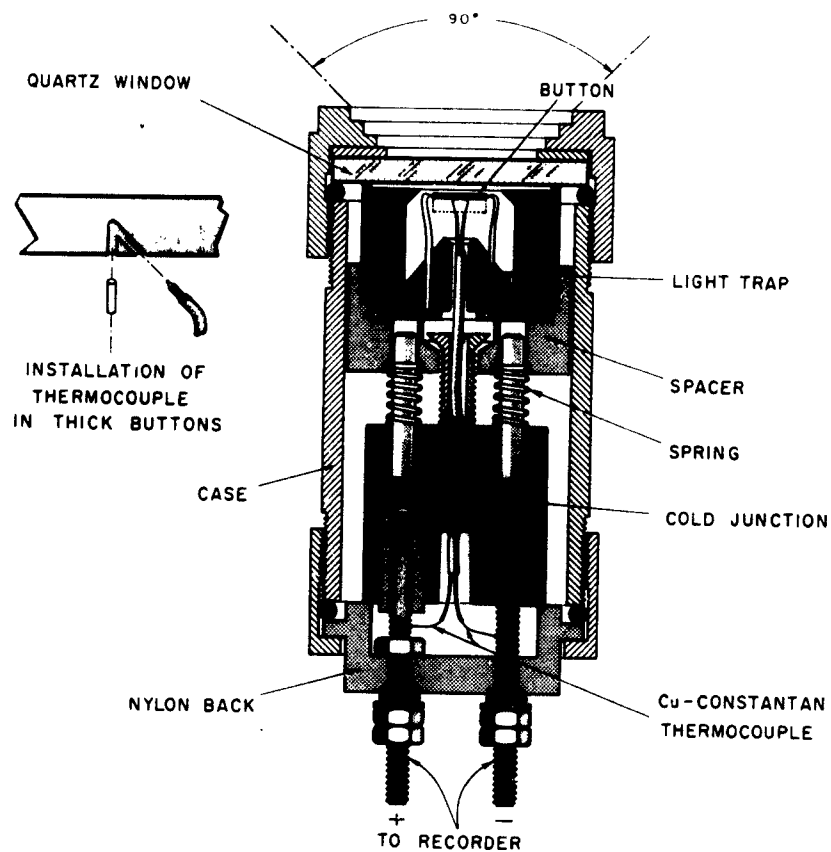
Fig. 1   Schematic drawing of NRDL standard calorimeter, used
         from 1953 through 1962. The NRDL tertiary standards
         are of this construction
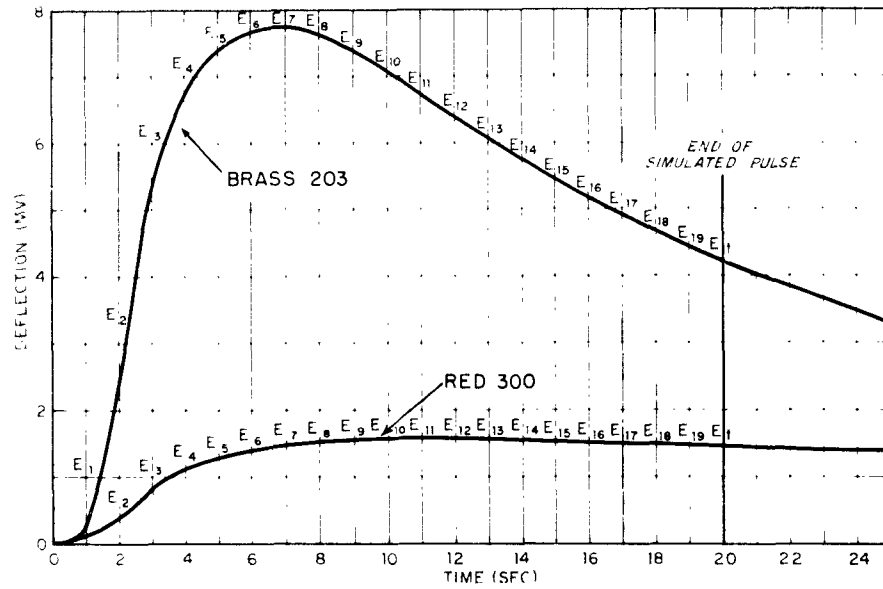
Fig. 2 Output of Two standard calorimeters to a simulated
4 MT thermal pulse
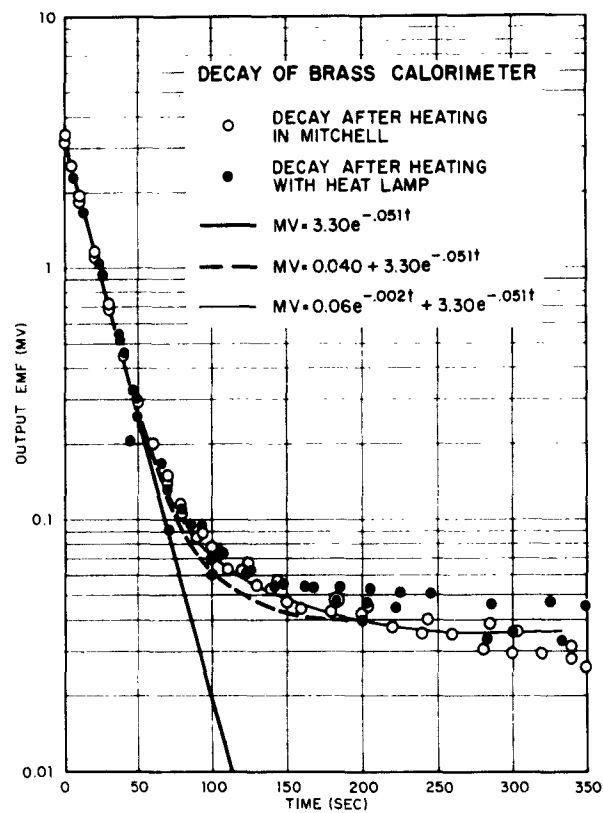
Fig. 3 Calorimeter decay. Curves are drawn to the equation, not through the points
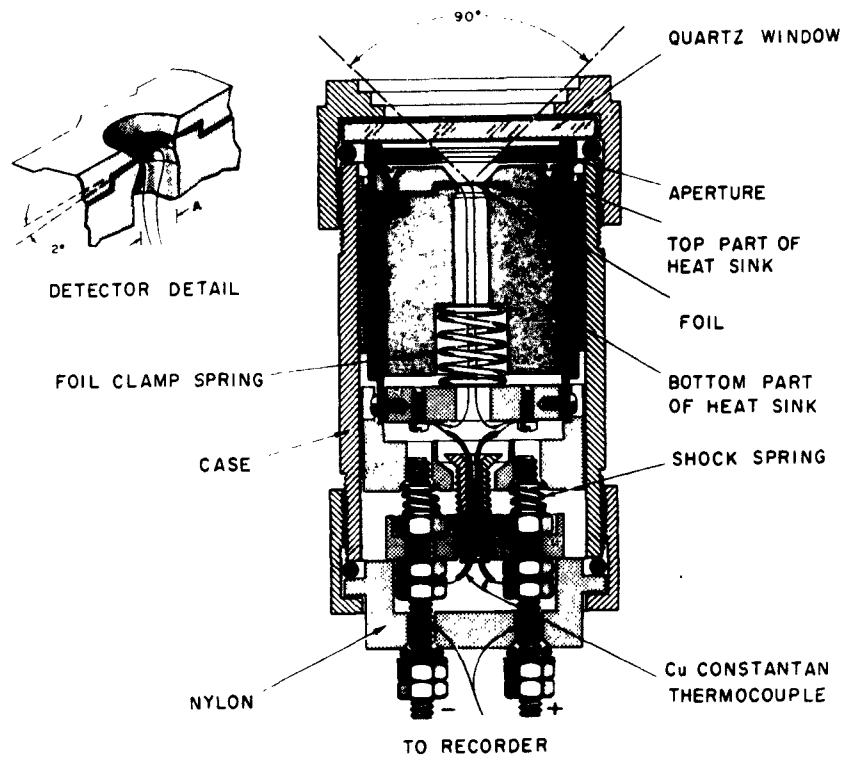
Fig. 4 Schematic drawing of NRDL spring loaded
radiometer, used in 1958 and 1962

Fig. 5 Photograph of 36" searchlight source

Fig. 6   Photograph of Mitchell source

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Fig. 7   Photograph of Brenkert source

DETAIL OF QUARTZLINE LAMP

SPRING LOADED CONTACTS

TO 115v AC

500w QUARTZLINE LAMP

CERAMIC SUPPORT AND INSULATOR

AW PASSAGE AND WIREWAY

AW PASSAGE AND WIREWAY

VARIAC

BLOWER

THIRTEEN 500w QUARTZLINE LAMPS

POWER SUPPLY & CONTROL BOX

ADJUSTABLE TABLE

VOLTMETER

SLIDING WAYS
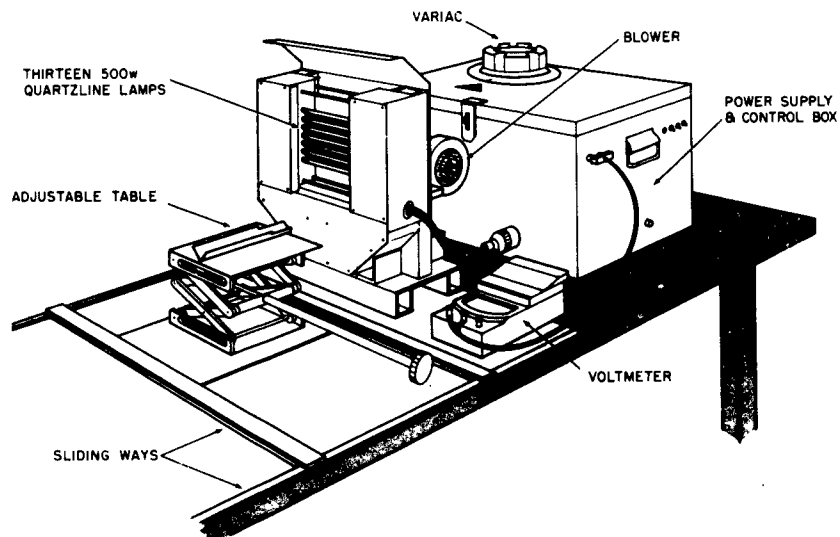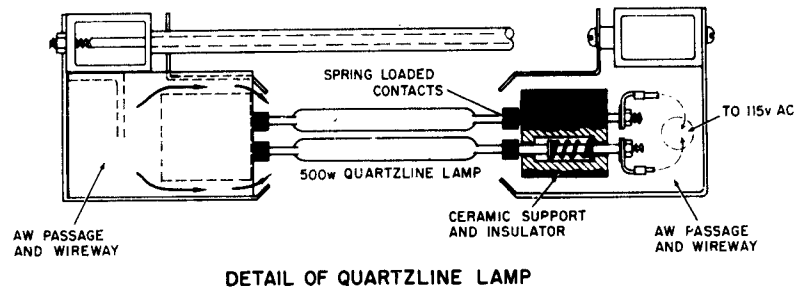
Fig. 8 Schematic drawing of tungsten source, showing lamp mounting details

Fig. 9 Photograph of Tungsten source

COPPER BUTTON

FUSED QUARTZ
FACEPLATE

CHROMEL WIRES

GRADED SEAL,
QUARTZ TO GLASS

CERAMIC SPACER
AND LIGHT BAFFLE

ALUMEL WIRE

O-RING VACUUM SEAL

TO
VACUUM

TO RECORDER
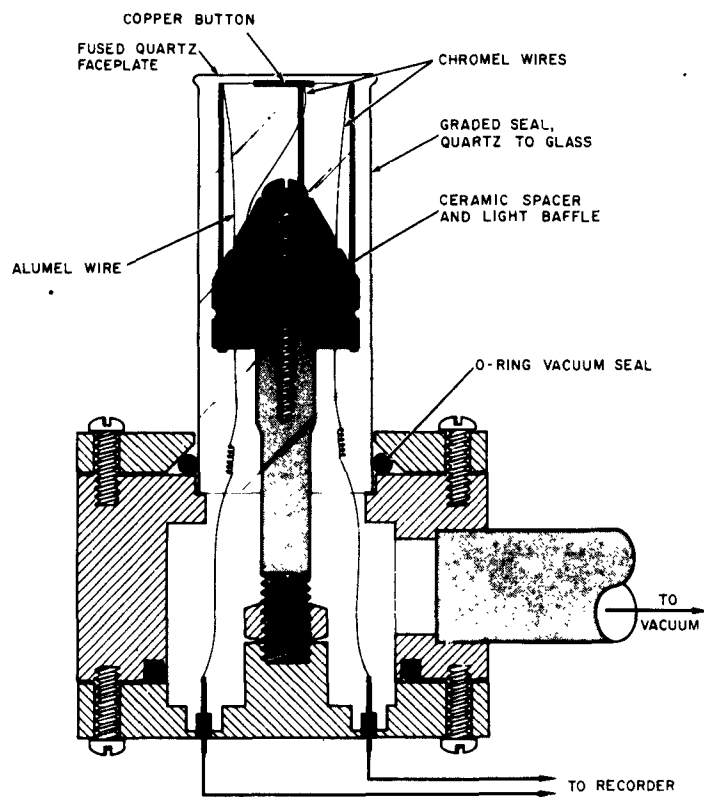
Fig. 10 Schematic drawing of phototype vacuum calorimeter

FOIL MOUNTING DETAIL

BEFORE
SPINNING

SEAT WALL
KNIFE-EDGE OF SEAT

AFTER
SPINNING
(ROLLED EDGE)

CENTER THERMOCOUPLE DETAIL

STAKE

PUNCH
SPLIT WITH SCALPEL
FOIL
ANVIL

EDGE THERMOCOUPLE DETAIL

PIERCED
HOLE

DETECTOR
FOIL SEAT

FUSED QUARTZ WINDOW
WITH INTEGRAL APERTURE

DETECTOR FOIL

SILVER FOIL
MOUNTING SEAT

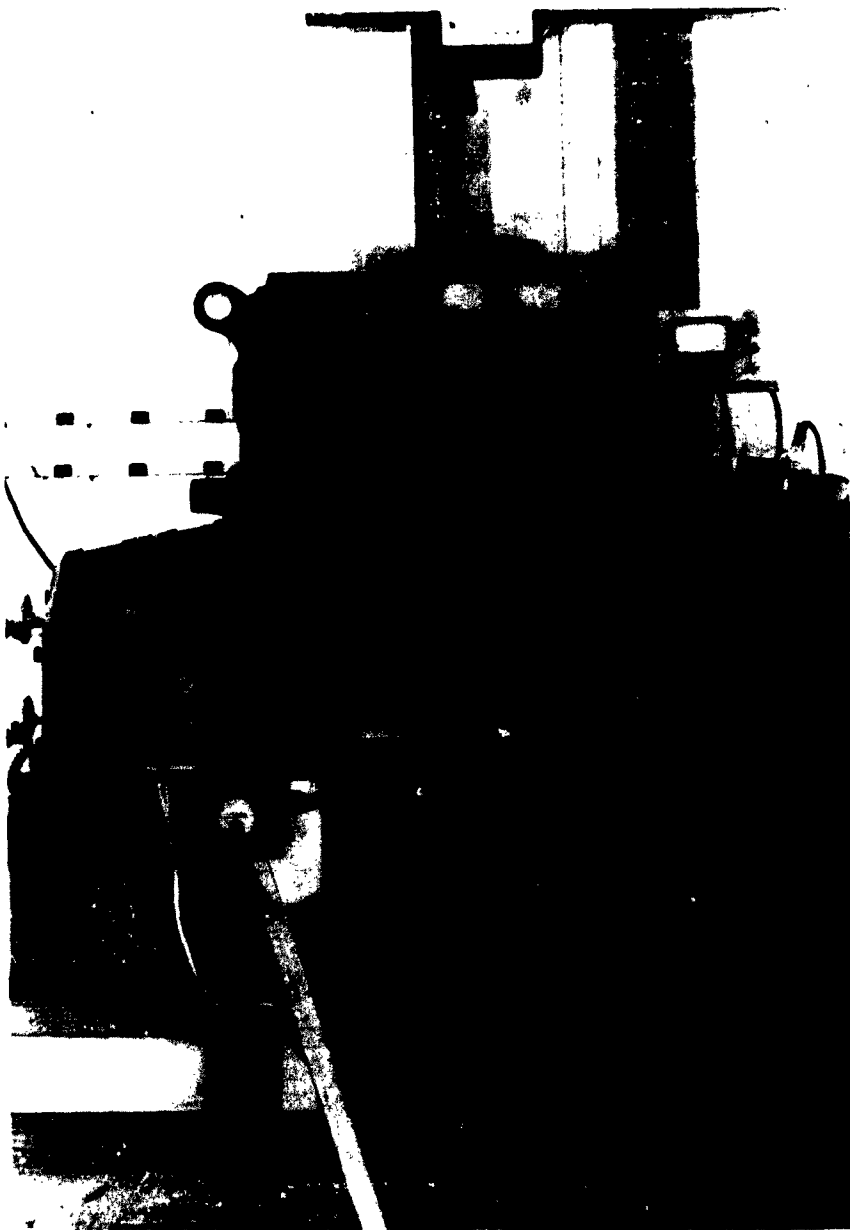KEL-F O-RING
MOISTURE SEAL

SLEEVE SUPPORT
AND CLAMP

COOLING WATER PATH

COPPER WATER BAFFLES

5 ML CONSTANTAN WIRES
IN TEFLON SLEEVES

SPARE WIRE

COPPER BODY
(GOLD PLATED)

WATERPROOF PLUG

CONNECTOR
TO RECORDER

WATER INLET

WATER OUTLET

Fig. 11 Schematic drawing of RLSW water cooled radiometer
with details of the foil mounting. The output
plug is waterproof and the cable comes out in the
exhaust water line

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FUSED QUARTZ WINDOW

APERTURE

SLEEVE SUPPORT AND CLAMP

O-RING SEAL

1 MIL SILVER DETECTOR FOIL

HEAT SINK

CONSTANTAN WIRES IN TEFLON SLEEVES

COLD JUNCTION

TO RECORDER

COPPER TUBING

WATER IN   WATER OUT
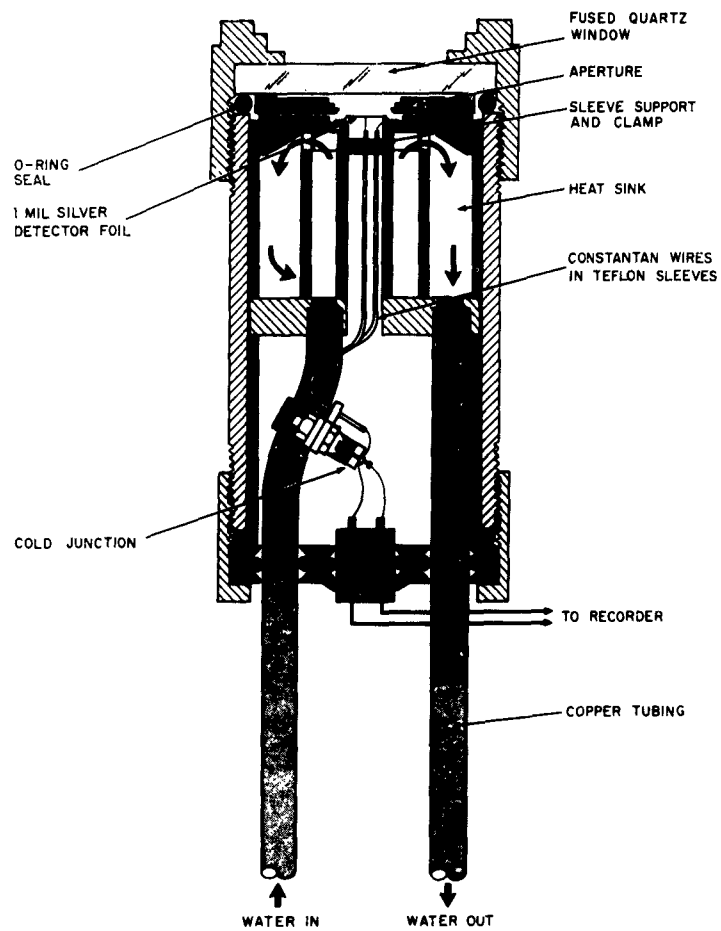
Fig. 12 Schematic drawing of laboratory water cooled radiometer

110°

1 MIL SILVER
DETECTOR FOIL

FUSED QUARTZ WINDOW
WITH INTEGRAL SILVER
PLATED APERTURE

HEAT SINK (COPPER)

CASE

INSULATING SLEEVE

O-RING SEAL

SLEEVE SUPPORT
AND CLAMP

5 MIL CONSTANTAN
WIRES IN TEFLON SLEEVES

AN 3102 M 14 S 25

TO RECORDER
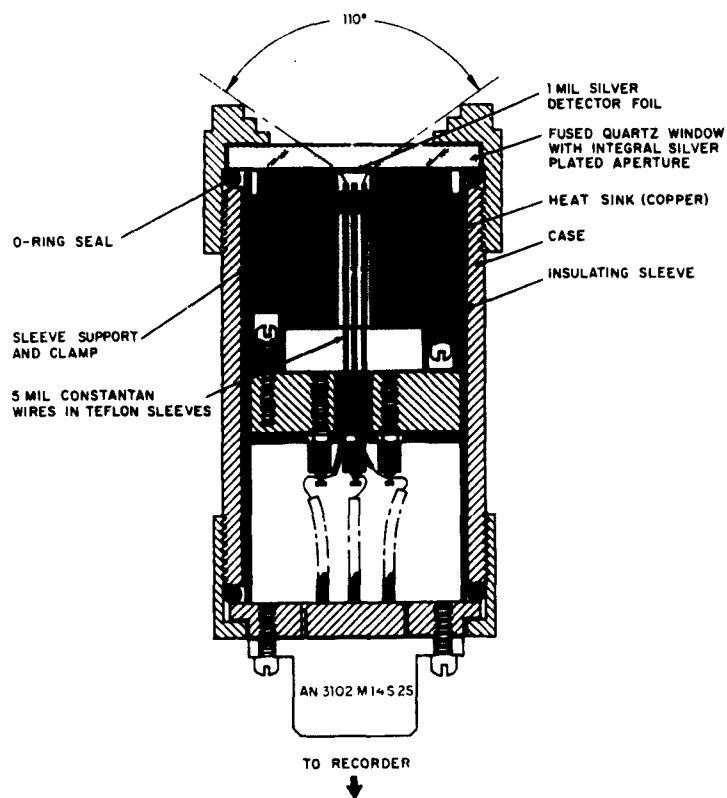
Fig. 13 Schematic drawing of RFS field radiometer

56

90°

FOIL

QUARTZ WINDOW

HEAT SINK

HEAT SINK

INSULATOR

CASE

INSULATOR - SPACER

SHOCK SPRING

SPACE

NYLON

Cu-CONSTANTAN
THERMOCOUPLE

DETECTOR DETAIL

TO RECORDER

Fig. 14   Schematic drawing of NRDL standard radiometer
used before 1957

57

Fig. 15   Schematic drawing of NRDL standard calori-
         meter with a dome to give a 180° field of
         view

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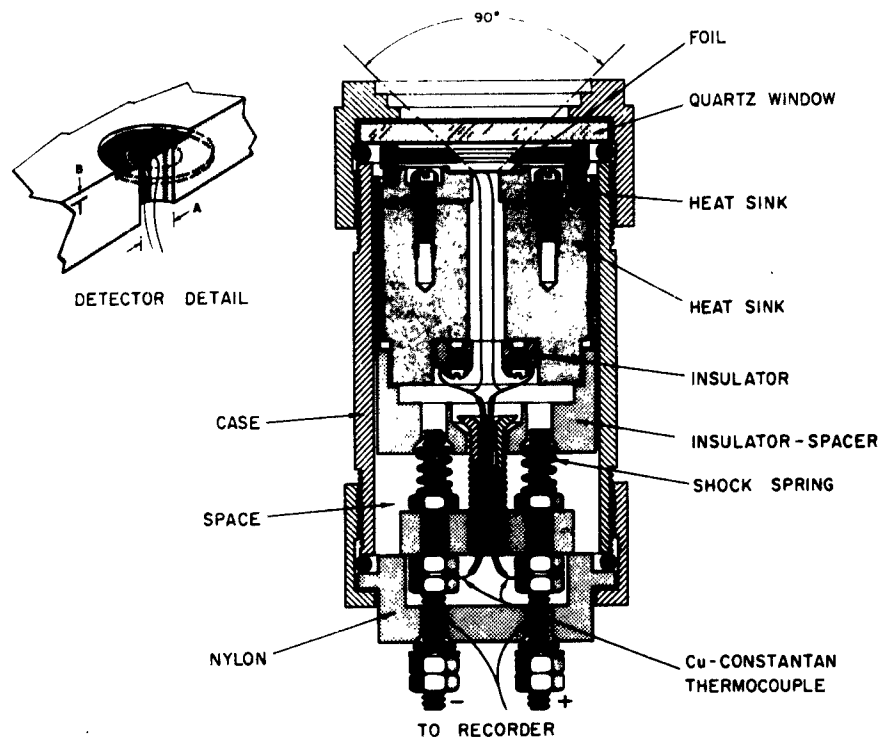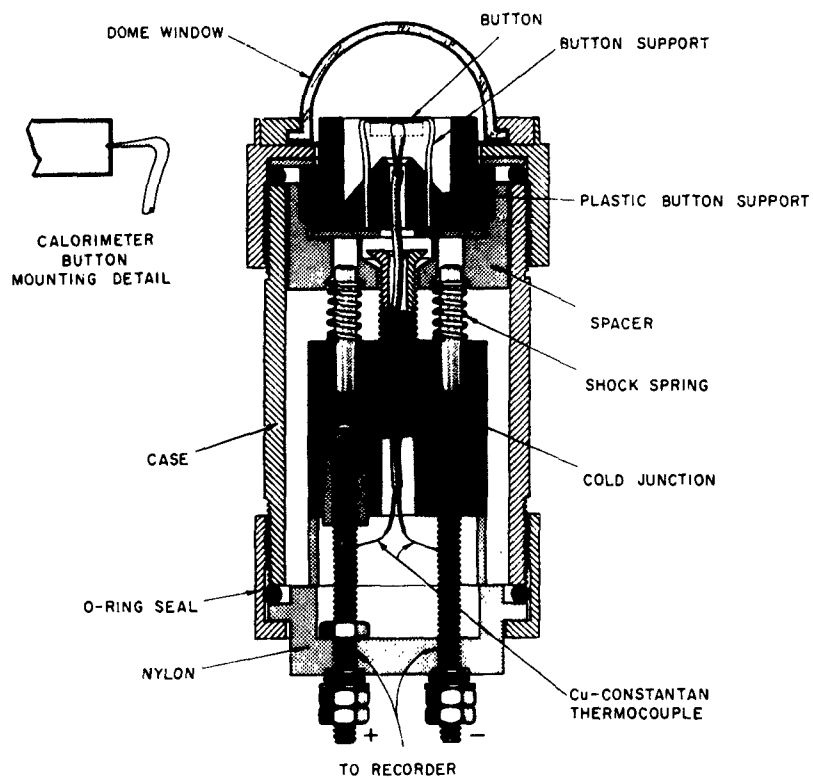
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The report is a general description of, and compilation of information about, the field type radiometers and calorimeters developed by NRDL to measure the total thermal energy and the radiant thermal power from nuclear detonations. Equations for deriving the sensitivities and time constants from physical parameters are presented and methods of construction and calibration are described. Information is also presented on laboratory sources for simulating thermal radiation from a nuclear weapon. Examples of data reduction from both field and laboratory sources are included.

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